Energy Recovery Considerations for Membrane Separation Process

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ABSTRACT

This paper gives an overview of different membrane processes like reverse osmosis, ultrafiltration, with direct and indirect energy recovery systems. The feasibility of using direct and indirect energy recovery in each membrane process and a few examples are presented. The importance of cogeneration technology and pervaporation, and principles and examples are also introduced.

INTRODUCTION

Membrane technology finds numerous applications in separation processes involved in water and wastewater treatment, medical and pharmaceutical industries, chemical processing, biotechnical applications, food and beverage processing, etc. It is becoming attractive and can substitute for conventional processes of separation like filtration, distillation, extraction, etc. Three major membrane processes used are reverse osmosis (RO), ultrafiltration (UF) and microfiltration (MF). RO is used for the separation of molecules because of its very small pore size (of the order of 10 A°) and it is extensively used in desalting brackish and sea water. UF and MF are used in removing macromolecules, colloids and suspended solids. There is an important difference between MF and UF with respect to the sizes of particles removed. The separation range of UF is between 0.001 to 0.05 μm whereas that of MF is 0.02 to 10 μm.

Pervaporation is another relatively new membrane process which is used to fractionate liquid mixtures (for example to concentrate alcohol from an alcohol-water solution). This process has thus a good potential of replacing the conventional thermal processes like evaporation, distillation with considerable energy saving.

Membrane processes need mechanical energy and in some cases, this can be very great, making the membrane processes unable to compete with classical processes in terms of energy. For example, RO requires as high as 60 bars of applied pressure for sea water desalination.

In membrane processes, the mechanical energy is required for two purposes:

- to increase the pressure of feed flow rate in order to obtain the pressure required for separation. A high pressure feed pump is required for this purpose.
- to decrease the boundary layer thickness in order to increase the mass transfer. For this purpose, a recycling pump is required.

For example, in a membrane process with recycle (Fig. 1), the energy required for feed pressurization can be given by:

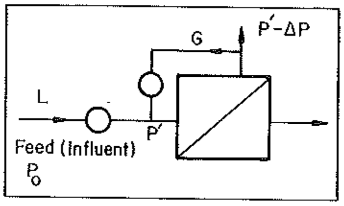

Fig. 1. Schematic pressure diagram of a membrane process.

$$L\,(P - P_o) = W_p \tag{1}$$

where L = feed flow rate (m^3/s)
$P - P_o$ = pressure difference (Pascal, Pa)
$P' - P$ = transmembrane pressure drop.

The recycled flow rate (G) is higher than the feed flow rate (L) and energy to be supplied here is only to make up the energy loss by pressure drop in the equipment, i.e.

$$G\,\Delta P = W_r \tag{2}$$

where W_r = energy loss.

Taking into account an efficiency factor (r) regarding the production of electricity from fuel, oil or coal through the electricity producing plant, one can write the following equation

$$W_p + W_r = Q\,r \tag{3}$$

where Q = thermal energy required for mechanical energy production.

The actual computation of energy in membrane process is still more complex than shown above, as heat pumps and energy recovery devices are used with them.

The aim of this paper thus, is to present an overview of different membrane processes with direct and indirect energy recovery systems.

DIRECT ENERGY RECOVERY FROM REVERSE OSMOSIS (RO)

RO Principle

RO is a membrane process which is used to separate dissolved solids of molecular range. Reverse Osmosis (RO) is a proven desalination process worldwide, which occupies approximately one third of the desalination market. The working principles and theory behind RO desalination system can be found elsewhere (Merten, 1966 and Walter, 1987). The main parameter of RO, the permeate density flux can be given by the following equation.

$$J = k\;(P' - P - \pi) \tag{4}$$

The above equation indicates that the flux (J) is positive for $P' - P$ greater than π. The osmotic pressure (π) is as high as 30 bars for sea water containing 35 g/l of NaCl. Therefore, it is necessary to consider recovering at least part of the energy lost ($L\pi$) which is a significant amount.

In one of the RO desalination plants in Key West island, offshore of the Florida peninsula, the raw water is taken from the Gulf of Mexico for processing municipal fresh water of 11,355 m^3/day. The raw sea water is pressurized to about 70 bars in the inlet side of RO; with 30% conversion, the outlet to drive a hydro turbine for energy recovery is adopted instead of discharging it directly back to the sea (Fig. 2). The energy recovered by this system was estimated to reduce the energy consumption of the high pressure pump by almost 33%.

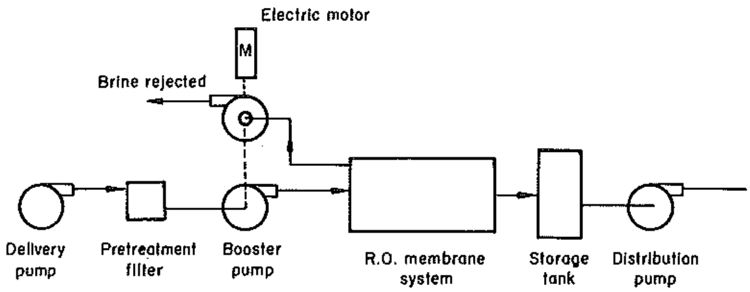

Fig. 2. RO plant with energy recovery.

A study of the capital and operating costs of an RO plant showed that, for a double pass RO system, the construction cost for an RO plant with energy recovery may differ only slightly from that without recovery, but, the energy and fuel cost savings may be up to 20 to 30% in the former system. Table 1 shows the items that are involved in this cost evaluation (Chiang, 1987).

Table 1. Cost breakdown of an RO plant (Chiang, 1987).

Item	RO double pass process		
	Without energy recovery	With energy recovery	% Saving
Construction	1.50	1.54	-2.66
Fuel and energy	1.14	0.90	21
Chemicals	0.14	0.14	0
Maintenance	0.05	0.05	0
Membrane substitution	1.23	1.23	0
Operation and maintenance	0.91	0.91	0
Total	4.97	4.77	4.02

Unit: US$/Kgal, for 2.5 MGD plant

The energy recovery in RO by means of a Pelton wheel or a hydroturbine becomes economical only in plants of more than 1 million gal/day capacity (Torrey, 1984). The only energy in terms of heat is generated by the pumping action of the process fluid. This makes the temperature of the circulating fluid in the pipelines go up to 70°C. In some applications heat energy has to be removed to avoid damage to the feed components. Various possibilities for the direct recovery of energy in RO processes are discussed in the following sections.

Hydraulic Turbine

Pelton turbine

Energy can be recovered from rejected brine using a Pelton impulse turbine. This is a wheel with buckets on its circumference. Fluid at high pressure hits the buckets with high velocity.

The capacity recovered by an impulse turbine can be used as mechanical energy, either by direct coupling of it (to the shaft drive of the feed water pump) or by using it to drive a synchronous machine to generate electricity. The turbine can also be directly coupled to the feed water pump. The turbine operates at an efficiency of 80 to 87% (Khan, 1986). This represents a saving of 40-60% of the energy requirement of an RO plant. The Pelton turbine is not usually connected directly to the high pressure booster pump, because the shaft speeds for optimum design are different.

Hydroturbine

A hydroturbine is a multistage, split case, backward running centrifugal pump. Hydroturbines are usually mounted and directly connected to the high pressure pump. The energy recovered is used to turn the high pressure RO pump. The efficiency is the same as the turbine/generator package mentioned earlier.

Biphase turbine

A biphase turbine is operated by a steam turbine and a water turbine. Energy from a high pressure hot water stream is flushed through a converging-diverging nozzle to the turbine unit. This turbine set is directly connected to a high pressure pump. Therefore, it eliminates the use of an electric motor. Normally, the operation of the steam turbine of the set is dependent on the availability of waste energy which can be supplied from diesel engine, or gas turbine recovered heat.

Work Exchanger

The principle of work exchanger is based on waste fluid flowing into the chamber from where it displaces the feed. Preheated feed water at low pressure is first fed into a cylinder which is then pressurized with reject brine at the other end. Feed water is then forced into RO modules by reject brine which is at high pressure.

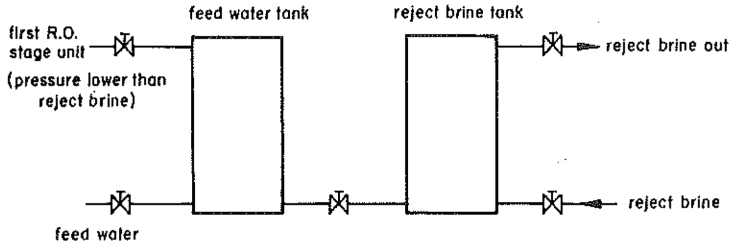

Fig. 3. The basic operation of the work exchanger.

INDIRECT ENERGY RECOVERY FROM ULTRAFILTRATION (UF)

UF Principle

UF is another membrane process which is used to separate macromolecules from liquid. The UF membrane allows the passage of water and low molecular weight solutes but retains macromolecules whose sizes are bigger than the pore size of the membrane. UF pore sizes usually range from 0.001 to 0.05 μm. UF enables concentration, purification, and fractionation of macromolecules in solution to be carried out at temperatures close to ambient temperature and without phase change or addition of solvents. This protects the biochemical structure activity of the product, giving increased yield over conventional separation technologies.

UF utilizes microporous membranes to separate macromolecules and suspended solids from solution on the basis of size, separating compounds with molecular weights from 1000 to 100,000 (1 to 100 nm in size).

The application of pressure of 1-3 bars (not as high as the RO process) to the feed side of the membranes enables the passage of water through the membrane. This makes the higher molecular weight compounds concentrate on the high pressure side, while the concentration of lower molecular weight compounds remains the same on both sides of the membrane. The direct recovery of energy as in the case of RO is not attractive or economical in the case of UF, since the pressure applied in the latter is much lower than in the case of the former.

Two basic operation modes, namely, batch and continuous, are used. In the batch system, the liquid is fed into the UF, permeate is withdrawn, and the concentrated liquid is returned to the feed tank. There may be a single pass or multiple passes through the membrane until the desired concentration or required purity is obtained. In a continuous system, the feed is continually supplied, and the number of stages and feed flow rate are determined, based on the required conversion ratio and required purity. A continuous multistage system is better than the single stage system because of its improvement in the average flux.

UF for Increasing the Efficiency of an Anaerobic Digester

UF, if coupled with an anaerobic digester, will increase the efficiency of the anaerobic digester by removing any by-product and by increasing biomass concentration. This can be represented by the following general relationship

$$\text{Waste} + \text{Microorganisms} \Longleftrightarrow \text{Biogas} + \text{By-product (BP)} \qquad (5)$$

The rate of production of biogas r_j is given by an equation of the following type:

$$r_j = f(C, Micro) - g(BP)$$

where f is an increasing function of concentrations of waste (C) and microorganisms, and

$g(BP)$ is an increasing function of the concentration of by-product (BP) which is removed by UF in order to decrease $g(BP)$.

In most cases, a digester is used as the wastewater treatment process. The incorporation of UF with an anaerobic digester would help to reduce the size of the reactor because of the shorter hydraulic retention time necessary. The smaller the size of the digester, the smaller the investment cost and the lesser the heat lost.

Application of the membrane solid/liquid separation anaerobic digester for recovery of methane gas is a known fact. The incorporated system called Membrane Anaerobic Reactor System (MARS) is a suspended growth anaerobic reactor followed by a membrane ultrafiltration unit for solid-liquid separation. The contents of the reactor are continuously pumped into the membrane unit, which can be retrofitted to an existing reactor. The permeate from the membrane unit goes as effluent. Therefore, in this case, no sedimentation facility is necessary. The solid retention time (SRT or θ_c) which can be controlled by sludge wastage from the reactor, varies from about 25 to 50 days, which is considered to be high compared to the conventional digester, i.e. the digester without membrane, in which the SRT normally ranges from 10 to 20 days. The operating conditions for the MARS pilot plants treating various wastes are shown in Table 2.

A Membrane Anaerobic Reactor System normally employs ultrafiltration (UF) since lower pressure is required. In this process, the biomass concentration is increased as high as 20,000 mg/l, which is impossible to achieve in a conventional solid/liquid separator. This leads to an increased gas production. Li *et al.* (1984) reported that for whey (sweet and acid whey permeate) and wheat starch wastewaters, the observed methane yield in m^3 CH_4/kg COD removed ranged from 0.28 to 0.34, whereas the theoretical yield is 0.35 m^3 CH_4/kg COD removed.

The methane gas generation rate may be estimated from the kinetic equations developed for the anaerobic digester (Equations 6 and 7 as given by Qasim, 1985).

$$P_x = \frac{YLES_o}{1 + K_d\theta_c} \tag{6}$$

and

$$V = a\,ELS_o - b\,P_x \tag{7}$$

From these equations, one can notice that the increase in SRT (by coupling of UF with digester) leads to a decrease in P_x and increase in V.

Smith and Talcott (1982) reported that for a single tank anaerobic digester fed with dairy waste, a retrofitted ultrafiltration unit (HFM-180) produced a steady state permeate flux of 35 l/m^2hr.

When the influent COD level was 17,000 mg/l, the effluent COD from the conventional separator was usually higher than 6,500 mg/l, but reduced to about 2,000 mg/l when UF was employed. The gas production was increased by an amount of 15-20%. One of the problems in

Table 2. Operating conditions for the MARS pilot plants treating various wastewaters (Li *et al.*, 1984).

Operating conditions	Types of wastes				
	Sweet whey	Sweet whey permeate	Sweet whey permeate	Acid whey permeate	Wheat starch wastewater
Volumetric loadings, kg COD/m³ d					
Range	7.4-8.8	3.9-16.3	7.5-10.7	9.3-9.7	8.0-8.4
Mean	8.0	14.6	8.5	9.6	
Solid retention time, days (d)	25	25	50	27	30
Hydraulic retention time, days (d)	7.1	1.93	7.38	5.71	4.38
Mean F/M ratio, 1/d	0.33	0.55	0.35	0.30	0.37
Reactor TSS concentration, g/l	27.2	35.3	32.4	36.5	24.1
Reactor VSS concentration, g/l	24.2	26.5	24.3	32.4	22.4
VSS/TSS, %	90	75	75	89	93

TSS = Total Suspended Solids
VSS = Volatile Suspended Solids
F/M = Food to Mass Ratio

single tank digester fitted with a UF system is the increase in concentration of acetic acid (i.e. a drop in pH) since methane forming bacteria digests more slowly than acid-forming bacteria. Therefore compartalization is always required which will also increase the methane gas yield. Similar to the conventional process, a two tank system is also employed with a methane related anaerobic digester.

Figure 4 shows the membrane controlled biogas process. The process is separated into two compartments, by adjusting the solid retention time of each tank, acidogenic and methanogenic reactions occur in the first and second tank respectively. The UF here is employed to concentrate the biomass, where UF1 allows the passage of acetic acid into the second tank, and UF2 provides a final effluent of low suspended solids content. The activated sludge process is usually used to polish the final effluent before the treated water can be discharged.

These types of idealized designs are becoming more attractive for some soluble, concentrated, industrial wastewaters as process economics has already been improved and greater savings in energy can be achieved. This treatment system not only emphasizes the treatment of the wastes, but also provides a useful means to recover energy in terms of biogas.

Other chemicals, e.g. ethanol and acetone, can also be recovered by employing a pure culture bioreactor. But up to now, not much work has been done by using wastewater as a feed.

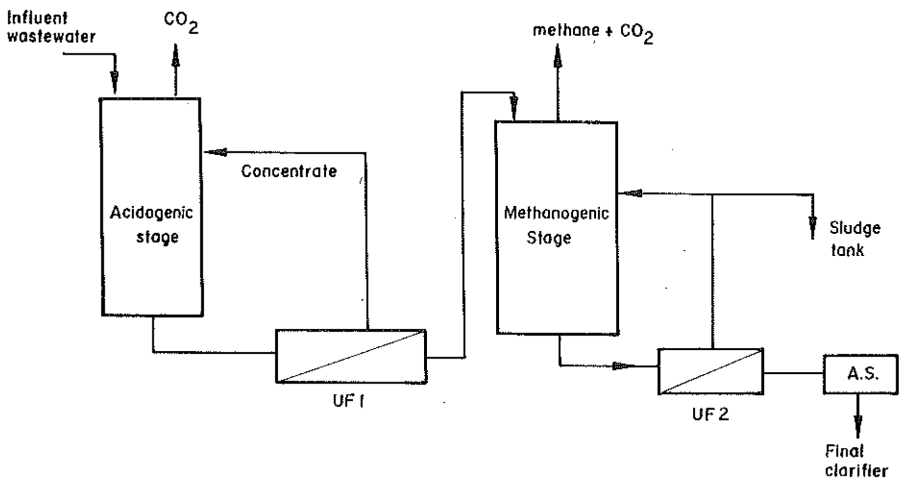

Fig. 4. Membrane controlled biogas process.

Synthetic wastewater containing mainly biodegradable sugars (glucose) and lactose has already been tested. Figure 5 shows the Membrane Recycled Bioreactor which can be used for this purpose. The membrane acts as a separation medium to separate the products (e.g. ethanol or acetone) which are considered to be toxic to bacteria. For this reason, the products must be withdrawn from the system as soon as they are produced so that bioreaction will continue to take place. One of the problems encountered in these types of reactors is the separation of products from the fermentation broth. Attempts have been made to incorporate chemical unit operations, like distillation and extraction with membrane based bioreactors, so that the required component in the permeate (from the membrane) can be separated accordingly since the fermentation broth is considered as a mixture rather than a pure component system (Cynthia, 1987).

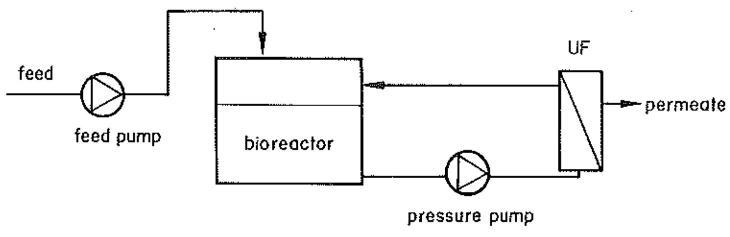

Fig. 5. Membrane recycled reactor.

One of the possibilities to produce ethanol on a large-scale basis is by using acid and enzymatic hydrolysis of cellulose obtained from vast and renewable resources, e.g. corn, sugar cane, sugar beets and saw dust. Ethanol not only serves as a chemical feed stock but also as a liquid fuel to obtain energy. But over 98% of this industrial ethanol is produced from the catalytic conversion of ethylene appearing in natural gas. Due to the increase in energy price, cost effective fermentors have to be designed, the fermentor using membrane separation offers a versatile choice for this situation. Under this condition, the fermentor as well as the membrane system are optimally designed. Pervaporation can be used to concentrate the alcohol content.

The conversion of cellulose to solvents like ethanol is the most possible conversion route in terms of energy resource recovery. The conversion with microbial enzymes and fermenting microorganisms is strongly regulated by product inhibition, the most potent inhibitor being the intermediate, cellobiose. In order to achieve a complete hydrolysis of cellulose, it is therefore necessary to continuously remove the hydrolysis products. In this case, membrane biotechnology can be employed to withdraw the fermented products. A continuous process for bioconversion of cellulose to ethanol is shown in Fig. 6 (Hahn-Hagerdal *et al.*, 1981). The conversion of glucose is taking place in the enzyme microbe reactor having ß-glucosidase co-immobilized with entrapped *Saccharomyces cerevisiae.* When a mixture of cellobiose and glucose from the enzyme membrane reactor is pumped through the enzyme microbe reactor, complete conversion to ethanol at a low dilution rate takes place.

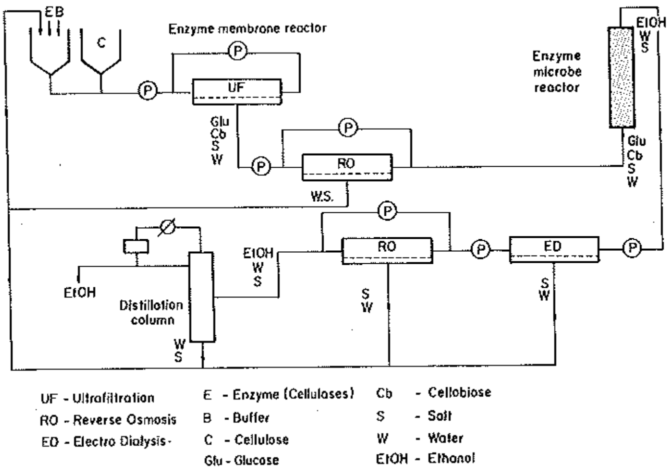

Fig. 6. Continuous process for cellulose conversion.

Recovery by Heat Pump System Combined to UF

Heat pumps have been used for several years for air conditioning and home heating. Due to increases in energy costs, heat pumps can be incorporated in membrane-based anaerobic digesters for energy recovery. It is beneficial to use UF separation systems when heat pumps are used because UF gives rise to an effluent practically without any solids content thus precluding any clogging problem in the heat exchanger.

Figure 7 shows a schematic diagram for heat recovery by using heat pump from a membrane based anaerobic digester.

The effluent leaving the ultrafiltration (UF) normally has a temperature of 35°C, which represents unrecoverable highest heat loss (HHL) from the process. By using a heat pump operating on an electric motor, the effluent temperature can be reduced from 35°C to 18°C. In the meantime, hot water at a temperature of 63°C can be produced from the heat of the effluent stream (Fig. 7). Here the hot water has many applications such as industrial hot water usage, preheating boiler feed

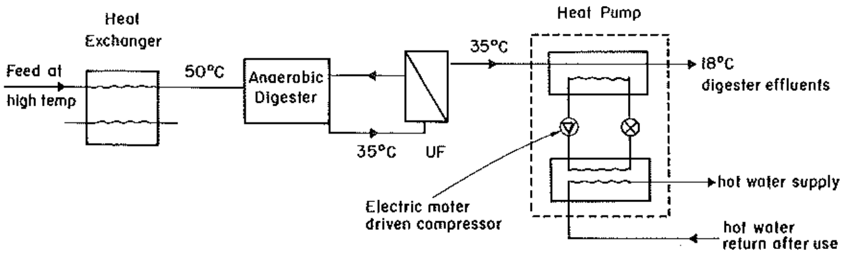

Fig. 7. Heat recovery in heat pump-membrane anaerobic digester system.

water, and preheating process feed streams.

Figure 8 shows another heat recovery system by using a two stage heat pump. The system is assumed to be totally insulated with zero heat loss (ZHL). Zero heat loss of course is not attainable, but this scheme was chosen as an ideal model of a heat recovery system. Schwartz *et al.* (1981) reported that for a total heating load in a wastewater treatment plant of 7.8 x 10^9 BTU/hr energy, HHL and ZHL systems can provide 38.6% and 63.7% of the heat load, respectively. The remaining heat required can be obtained by using a fuel boiler or a gas boiler.

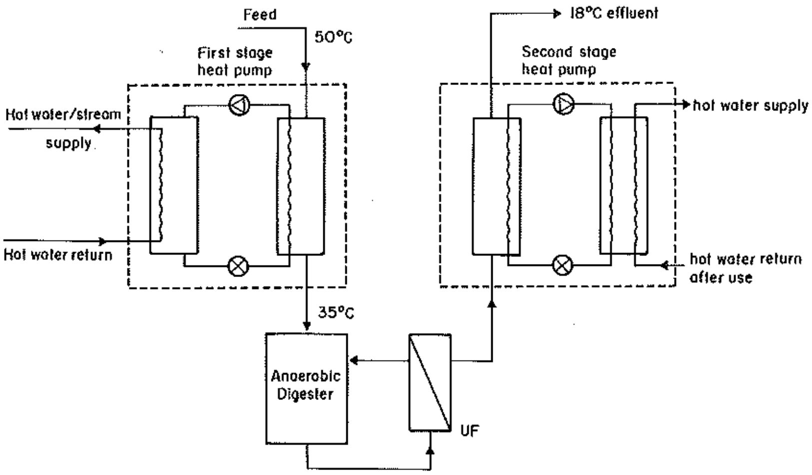

Fig. 8. Heat recovery by heat pump using zero heat loss (ZHL) technique.

The climatic surroundings of an anaerobic digester is important. Figure 7 is for European or North American conditions. For tropical conditions, the surroundings temperature and feed temperature are higher and losses are thus lower. Therefore, efficiency of the heat pump is higher for the same temperature of hot water in tropical conditions.

Membrane Process and Cogeneration

Cogeneration is a technology which permits the simultaneous provision of the steam and electricity required by the membrane process. For this purpose, steam at a higher pressure than the pressure required by the process is produced. Steam is expanded through a turbine to the required process pressure. The expansion provides the work used for producing electricity.

The technology provides sometimes more electricity than the quantity required by the process, for example in the case of the pulp and paper industry. This excess electricity can be sold to the grid, but the selling price is of course less than the buying price as the cost of distribution is not borne by the factory which is producing the extra amount of electricity. Moreover, due to load management of the grid, selling electricity is often not allowed by government regulations in many countries. These two points are, of course, inhibiting interest in cogeneration.

This additional electricity produced can be used within the factory to increase product output or product quality and to decrease any pollution arising from production processes. Membrane technology is useful in this kind of application. For example, in a pulp and paper mill, excluding black liquor, wastewater is also generated in dust separator, screening, thickener, filter and bleaching stages. The wastewater is large in quantity and coloured. Conventional waste water treatment cannot remove colour. Membrane technology can therefore be used to treat these wastes.

As an indication of the benefits obtained from cogeneration, in a pulp and paper industry producing 40 ton/day of paper with an average water consumption of 12,740 m^3/day, the power required is 800 kW. The cost of pumping energy is estimated to be US$1,240/day against US$740/day from cogeneration. This plant is able to produce 1,700 kW from cogeneration (Xu, 1988).

PERVAPORATION AND HEAT PUMPS

Pervaporation Principle

Pervaporation is a membrane process which is used to fractionate liquid mixtures. The separation is done through a vaporization process in the membrane (Aptel *et al.*, 1976; Gooding and Bahouth, 1984).

The driving forces are temperature and pressure difference. Vacuum conditions are needed on the vapor side. One of the consequences is that condensation occurs at a low temperature (0°C or below) and refrigeration is needed.

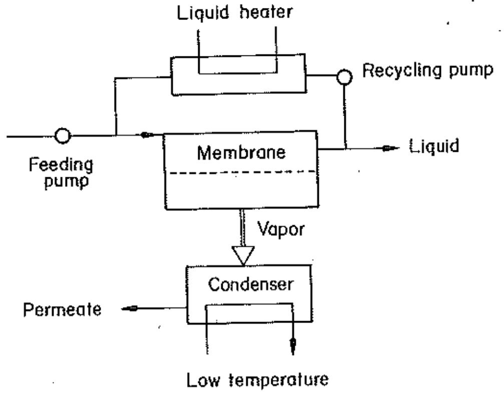

Fig. 9. Pervaporation without heat pumps.

The heat of vaporization necessary for the pervaporation process is taken from the liquid phase which is at a higher temperature (but temperature is below 50°C, as membrane are usually made from polymers).

The recycling energy is transferred into heat through friction within the fluid which contributes to the heat balance for fluid heating.

Pervaporation Coupled to a Heat Pump

It is interesting to use a heat pump in order to increase the efficiency of the system. The pervaporation systems with and without a heat pump are shown in Figs. 9 and 10.

The cold source of the heat pump is the condenser of the pervaporator and the hot source is the liquid heater.

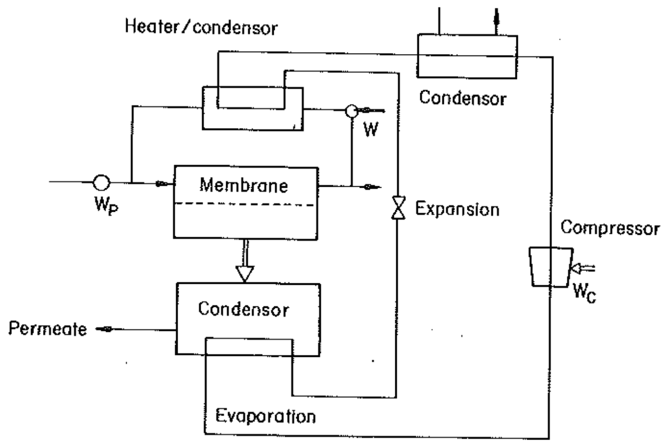

Fig. 10. Pervaporation with heat pumps.

The heat balance on the heat pump can be given by the classical first and second laws of thermodynamic balances. But in this case our interest is in the cold source rather than the heat source.

$$\frac{Q}{W} = \frac{T}{T'-T} = R_T n = COP' \tag{9}$$

If one assumes that the energy required for liquid heating, is equal to the energy required in the condenser Q, then it appears that too much heat is supplied by the heat pump to the liquid: which is $Q + W$. In fact, we have to add the mechanical energy for pressurization and recycling. The surplus q is given by:

$$q = W_c + W_p + W_r \tag{10}$$

This surplus energy can be used partly for the increase of liquid feed temperature. Any energy remaining can be rejected to the surroundings.

If this temperature is less than 50°C, this energy is not useful. If it is more than 60°C, this can be used for supplying hot water.

Heat can be recovered from the outlet effluent in order to preheat partially the inlet feed. This can only be used to increase the efficiency of the system if the excess heat can be made available.

One has to note that the work consumption is directly linked to the temperature difference between T' and T.

CONCLUSION

Membrane technologies are found to be more attractive than conventional thermal process like evaporation or distillation as this technology uses less thermal energy. On the other hand since they replace thermal energy by mechanical energy mainly through electrical energy, one must take account of this factor also in energy consumption calculations.

It has been shown in this paper that, there exists technology in order to reduce the energy consumption in the membrane processes. These processes can also be directly used to improve the energy efficiency of the processes (like biogas plant).

More generally, membrane technologies are currently included in various applications which permit a rational use of energy.

NOTATIONS

a	coefficient (dimension defined by Eq. (7))
A	area of the heat exchanger surface (m^2)
b	coefficient (dimension defined by Eq. (7))
C	concentration of waste useful for fermentation (kg/m^2)
COP, COP'	coefficient of performance of heat pump, refrigeration respectively
E	efficiency of waste utilization, 0.6-0.9
f	function (kg/m^3 s)
g	function (kg/m^3 s)
G	recycling flow rate (m^3/s)
k, k'	heat transfer coefficients (J/s m^2 K)
J	mass flux (kg/m^2 s)
k	membrane constant (kg/s m^2 Pa)
Kd	endogeneous coefficient (day^{-1})
L	liquid flow rate, inlet (m^3/s or m^3/d)
$Micro$	concentration of microorganism (kg/m^3)
n	efficiency of the cycle compared to the theoretical efficiency
P_o	surroundings pressure (Pa)
P, P'	inlet, outlet pressure (Pa)
P_x	net mass of cell produced (kg/s or kg/d)
q	excess heat (power) from mechanical energy (J/s)
Q	thermal energy (power) needed for mechanical energy production (J/s)

Q'	heat (power) produced by the heat pump (J/s)
r	efficiency factor (between 0.20 and 0.30)
r_j	gas production rate (kg/m^3 s)
R_T	theoretical (Carnot) efficiency
S_o	ultimate biological oxygen demand of influent waste (g/m^3)
T', T	higher and lower temperature (K)
U	overall heat transfer coefficient (J/s m^2 K)
V	volume of methane produced (m^3/s or m^3/d)
W_p	mechanical energy (power) for pressurization (W)
W_r	mechanical energy (power) for recycling (W)
W_c	mechanical energy (power) for compression (W)
Y	yield coefficient

Greek letters

P	: pressure drop (Pa)
π	: osmotic pressure (Pa)
θ_c	: cell residence time (s or d)

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